Physical and Chemical Properties of Vertisols and their Management

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Abstract

Vertisols, because of their high water-holding capacity, are suited to dryland crop production in semi-arid environments with uncertain and heavy rainfall, Selected physical and chemical properties of Vertisols that affect their' management for crop production are discussed. Due to their high clay content, the physical properties of Vertisols are greatly influenced by moisture content; usually, these soils are too sticky and unworkable when wet, and very hard when dry. The soil moisture range in which the physical condition of Vertisols is suitable for tillage and planting operations is quite narrow. Deep Vertisols have impeded drainage in the rainy season with consequent loss of trafficability; poor air-water relations are suspected. Land management practices that facilitate drainage and improve aeration, water intake and permeability of these soils need to. be evolved. Though generally of low fertility status, Vertisols offer opportunities for better crop production in semi-arid areas with erratic rainfall compared with other soil orders found in these regions; this is mainly due to their high moisture-holding capacity which allows crops to grow or survive for longer periods.

Vertisols are a group of heavy-textured soils which occur extensively in the tropics, subtropics and warm temperate zones and are known as Dark Clays, Black Earths, Black Cotton soils, Dark Cracking soils, Grumusols and Regurs in other classification systems (Dudal 1965). The major areas of Vertisols are found in Australia (70.5 mha), India (70 mha), Sudan (40 mha), Chad (16.5 mha) and Ethiopia (10 mha); these five countries contain over 80% of the total area of 250 mha of Vertisols in the world (Table .1).

Although Vertisols cover only a small area of the world's land surface, and only a sub-dominant portion even of any geographical zone, they are an important soil order in semi-arid dryland agriculture because in this environment they are amongst the most productive soils. The major factor contributing to the productivity of Vertisols in semi-arid environments is their high water-holding capacity; in areas of uncertain and variable rainfall, sometimes too much and often too little, the ability of a soil to store sufficient water to carry crops through droughty periods is of great importance.

However, some characteristics of these soils" do pose some problems for the cultivation of crops and some of the problems assume greater importance where

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Table 1. Distribution of dark clay (Vertisol) soils.

Country	Regions	Total area covered in million ha	Percentage of total area
Australia	Parts of Queensland, northern New South Wales, South Australia, Coastal areas of Northern Territories and Tasmania	70.5	28
India	Central and South-central areas of Deccan Plateau (mainly Andhra Pradesh and Madhya Pradesh states and a part of Maharashtra, Gujarat and Karnataka state)	60.0	24
Sudan	Regions between the Blue and White Nile. Widespread in South Sudan, Upper Nile and Equatoria Province.	40.0	16
Chad	Mainly areas in Chad basin but scattered patches in other parts	16.5	7
Ethiopia	Areas covered by the Rift valley and Ethiopian plateau	10.0	4

Source; Dudal (1965).

the farmer has only small holdings and limited resources. Because of these soil and socio-economic problems, the attainable production potential of these soils is commonly not met. This paper will therefore ,give emphasis to the physico-chemical soil factors that are important for agricultural management, especially for resource-poor farmers.

Definition

The definition of a Vertisol varies with the classification systems used, but for convenience we have used the one adopted in India (U.S. Soil Taxonomy): 'Vertisols are mineral soils that have a mesic, isomesic or warmer soil temperature regime; that do not have a lithic or paralithic contact or petrocalcic horizon or duripan within 50 cm of the soil surface; that, after the upper soil to a depth of 18 cm has been mixed, have 30% or more clay in all horizons down to a depth of 50 cm or more; that at some period in most years have cracks that are open to the surface or to the base of a low layer or surface crust and are at least 1 cm wide at a depth of 50 cm unless the soil is irrigated; and that have one or more of the following characteristics: (a) gilgai; (b) at some depth between 25 cm and 1 m, slickensides close enough to intersect; or (c) at some depth between 25 cm and 1 m, wedge-shaped (sphenoid), structural aggregates whose long axes are tilted 10° to 60° from the horizontal.' Inevitably, some inconsistencies arise when data are compared from sources using several different classification systems; nevertheless, the above illustrates the major point in all classifications—that physical characteristics of Vertisols are particularly important, especially their water-holding capacity, which in turn reflects their ability to store water by swelling.

Physical Properties

Texture

The basic property of Vertisols that endows them with a high moisture-holding capacity is their clay content, which commonly lies between40 to 60%, but it may be as high as 80% (Dudal 1965, De Vos and Virgo 1969). Generally, the texture of the surface soil is lighter and the clay content increases with increasing depth towards the subsoil (Butler and Hubble 1977). The clay content of Vertisols remains uniformly high (>35%) throughout the profile to a depth of at least 50 cm or more (Raychaudhuri et al. 1963; Dudal 1965; Yule and Ritchie, 1980a). In some Vertisols where the top soil is probably eroded, the clay content may be 40% or less, leading to loam or silty loam texture in some Vertisols in West Africa, and possibly even a sandy texture in the sub-surface (see Cocheme and Franquin 1967). Similarly, De Vos and Virgo (1969) reported a coarse texture in Vertisols in the Guneid and North area of the Blue Nile plains of Sudan, and attributed this to a parent material of Nubian sandstone.

Clay Mineralogy

The dominant clay mineral in most , of the Vertisols appears to be montmorillonite. This, plus the high clay content, appears to be the main reason for the high water-holding capacity of Vertisols. In Sudanese Vertisols, montmorillonite accounts for over. 90% of the clay fraction (Jewitt et al. 1979). In Indian as well as in Ethiopian Vertisols, montmorillonite is the dominant clay mineral (Khanna 1966; De Vos and Virgo 1969; Chatterjee and Rathore 1976). Limited data on Australian soils indicate that soils regarded as Vertisols contain clay that varies from being dominantly montmorillonitic in northern (tropical) environments to a dominantly illite/kaolinite mixture with some interstratified material in southern (temperate) environments (Norrish and Pickering 1977), The high negative charge of the clays in the northern soils reflects the change in mineralogy. The swelling of these soils is presumably due to intercrystalline swelling within,"domains" of clay crystals (Emerson 1959; Aylmore and Quirk 1960).

Few measurements have been made of surface area; the total surface area of the clay fraction as determined by the ethylene glycol monoethyl ether (EGME) method ranged from 628 to 770 m^2/g. (Chatterjee and Rathore 1976).

Available Water

Vertisols have a, relatively high water storage capacity in the root zone because of their usually high content of clay—dominantly a 2:1 type—and have a relatively deep soil profile. The available water range of Vertisols has been reported as 110 mm in Australia (Stace et al. 1968); 125 mm in the Sudan (Jewitt et al. 1979), and 230 mm in India (ICRISAT 1978) for the toper metre depth of the soil profile. It has been observed that the moisture content in deeper layers of the soil profile decreases, apparently due to compression effect on matric potential (Virgo and Munro 1978; Table 2).

Table 2. Soil moisture retention characteristics of a Vertisol from Tigrai, Ethiopia (pH 7.8, organic C 1.2%, clay 54%, $CaCO_3$ 8.3%).

Soil sample depth (cm)	Moisture retention (% volume)				
	0.0 bar	0.1 bar	0.3 bar	1.0 bar	15.0 bar
0.20 - 0.25	57.1	51.3	50.0	47.2	29.3
0.45 - 0.50	54.5	48.2	46.6	44.3	30.5
0.95- 1.00	47.9	39.6	37.8	34.6	17.6

Source: Virgo and Munro (1978).

A typical deep Vertisol at Hyderabad may therefore be able to hold as much as 250 mm of available water for crop production once the profile is fully charged (Figure 1). This contrasts with the much lower capacity to hold water of nearby related shallower soils (Vertic Inceptisols and Inceptisols) and nearby deep Alfisols, which can rarely store more than 150 mm.

The soil water storage capacity is particularly important in semi-arid regions with uncertain rainfall distribution. Based on the changes in the estimates of week-to-week changes in available moisture in relation to potential evaporative demands, Krantz et al. (1978) concluded that the growing season on a deep Vertisol at ICRISAT Center was 21 to 33 weeks, whereas it was only 14 to 21 weeks on the nearby Alfisol.

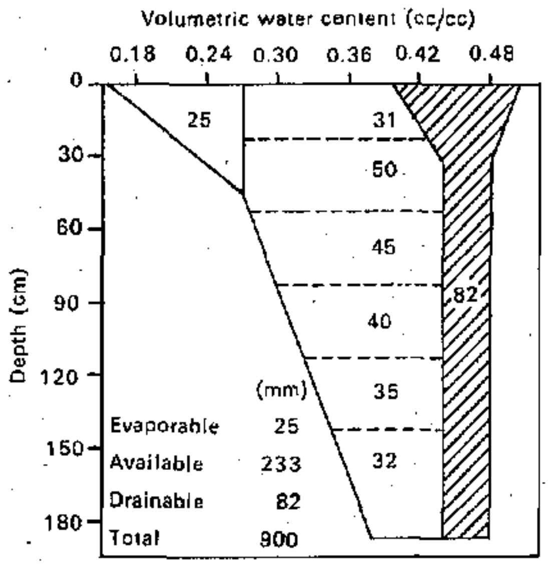


Fig. 1. Drainable, evaporable, and available water profiles of a deep Vertisol at ICRISAT Center, Hyderabad, India.

Phenomena Associated with Swelling and Shrinkage

In Vertisols storage of moisture causes swelling; loss of water causes shrinking. The relationship between loss of water from the soil and change in soil volume has been divided by Yule and Ritchie (1980a, 1980b) into three distinct phases:,

1. Structural shrinkage, in which loss of water from very wet soil occurs from only the very large pores and air replaces water during drying; there is no change in overall soil volume.
2. Normal shrinkage, in which loss of water between matric potentials of-0.3 and -15 bars; this shrinkage is equidimensional, allowing the calculation of a "Coefficient of Linear Expansion (COLE)".
3. Residual shrinkage, in which loss of water below matric potentials of about -15 to -20 bars occurs from between domains of calcium-saturated montmorillonite crystals and is not accompanied by any very substantial volume change; water loss is accompanied by air entry into the intra-domain (inter-crystalline) spaces.

The net result of these three phases is that the major shrinkage of soil over most of the available water range in the field occurs only by gradual contraction of the peds, without entry of air within the peds; hence, the obvious visible sign is widening of cracks between the peds. However, the initial and final phases, at matric potentials of -0.3 and -15 to -20 bar, are associated with little or no swelling, and water loss is associated with a corresponding volume of air entering large pores and domains respectively.

The cracking patterns, as observed at the soil surface, have been recorded (Fig. 2). Beds approximately hexagonal in shape (at the surface) are observed in the absence of any directional influence but, where crops are in rows, major cracks commonly predominate parallel to the crop rows, and mid-way between them; much smaller cracks within the crop row. This pattern has been attributed to the proliferation of roots holding the soil together {Johnston and Hill 1944; Johnson 1962; Fox 1964b).

Several other structural phenomena of Vertisols are attributed to the swelling and shrinking of the soil with changes; in moisture content, although the exact mechanism may not be clearly understood. These are gilgais, slickensides, sphenoid structural aggregates and self-mulching surface soils. It has also been noted that cultivation activities at times mark the development of gilgai (Finck 1961; Dregne 1976).

The name Vertisol derives from the fact that soil movement with changes in moisture content does not occur only in pressures and movements in the horizontal and vertical planes, but also occurs in directions between these planes. This gives rise to sphenoid structural aggregates—wedge-shaped aggregates and also slickensides the faces of peds that become polished due to regular movement against each other.

However, perhaps the most interesting feature of Vertisols is the development in some members of gilgais, which refer to the surface topographic phenomena of alternate mounds and depressions, with the intervening area between these being termed a shelf. A number of different forms in gilgais have been described

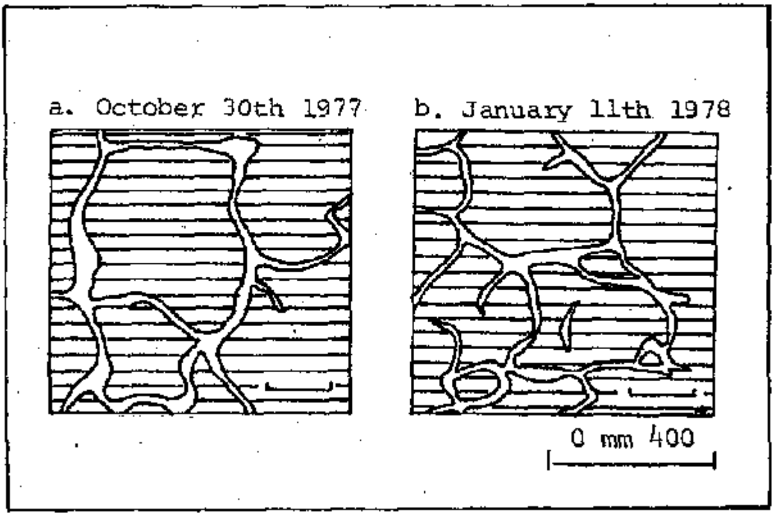


Fig. 2. Surface cracking pattern of bare soil before and 2 months after complete saturation of the profile, (Source: Virgo 1981.)

('normal' or round, mehen hole, lattice, linear, tank and stony) and many mechanisms suggested for their genesis; considerable attention has been given to the one based on uneven swelling and contractions of the soil (see Hallsworth and Beckmann 1969).

Gilgais and extensive deep cracks cause two characteristic properties of Vertisols. The cracks provide a means of rapid ingress of water deep into the soil profile, until these channels are closed by swelling of the soil. The gilgais cause a regular heterogeneity, with the mounds generally being more alkaline than the depressions or shelfs. This causes some complications in reporting data, because only a few of the earlier workers report data for both mound and shelf (or depression).

Consistence

Vertisols offer extremes of consistence—they are very hard when dry and very sticky and plastic when wet (Jewitt et al. 1979). Extreme hardness when dry and stickiness and loss of trafficability when wet, permit tillage and seedbed preparation only within a very narrow range of moisture contents. The cultivation of Vertisols when too dry or too wet may therefore result in poor tilth due to cloddy or puddled structure, respectively (Dudal 1965; Krantz and Sahrawat 1974; Krantz et al. 1978).

Bulk Density

The bulk density of Vertisols varies greatly because of their swelling and shrinking nature with changes in soil moisture content. The soils have high bulk density when these are dry, and low values when in a swollen stage. According to.

Jewitt et al. (1979), the bulk density of a Vertisol may vary from approximately 1 to 2 g/cm^3 depending on the moisture content. Bulk density usually tends to increase with depth, due to compression caused by overburden weight. Profiles of Arkansas and Mississippi Vertisols showed bulk density values ranging from 1.81 to 2.08, while Vertisols in Texas (Houston clay) reportedly had values varying from 1.59 to 2.1 (Dudal 1965). Yule and Ritchie (1980a) studied the soil shrinkage relationships of Texas (USA) Vertisols and reported that at the swelling limit the gravimetric water content decreased and bulk density increased with depth. They found that the depressions at the two gilgai sites had higher

Table 3. Comparison of the observed (at variable soil water contents) and the corrected bulk density (at 25% W/W) of different soil layers.

	Bulk density (g/cm^3) in relation to soil depth (cm)				
	0-10	10-20.	20-30	30-40	40-50
Observed	1.85	1.68	1.68	1.65	1.65
Corrected	1.50	1.41	1.44	1.46	1.44

Source: Rao et al. (1978).

water contents and lower bulk densities at the swelling limit than the mounds at all other depths. Similarly, Rao et al. (1978) observed a volume change of nearly. 60% when a dry Vertisol from Hyderabad was saturated with water. These authors suggested that the bulk density of such soils should be corrected to a chosen reference moisture (25% W/W) to minimise errors caused by the initial moisture content of the soils. This is well illustrated by their data (Table 3). The physical properties of Vertisols due to montmorillonite dominance, such as surface area, expansion and water-holding capacity, have been discussed by several authors (Biswas and Karale 1974; Ghosh and Raychaudhuri 1974).

Structure

The Vertisols possess inherently poor structure which is greatly influenced by water regimes. Krishna and Perumal (1948) described the formation of a 'lentil-like' (resembling lentil seed) structure having the shape of a double-convex lens in the subsurface of black cotton soils from the Hyderabad (India) area. The lentils formed are stable and of different sizes, which break into irregular or prismatic clods. Studies of the Blue Nile clay plains of Sudan indicated that the unequal pressures which result from the swelling and shrinkage processes are responsible for the aggregated structure (De Vos and Virgo 1969)

Infiltration Rates

Due to the presence of cracks at the beginning of the wet season, Vertisols have initial high infiltration rates which decrease drastically with increased wetting of the soil. One example of the decrease with time is given is Table 4; infiltration rates into a deep Vertisol decreased from 34-45 mm/h for the first one hour to

4 mm/h over 1 to 2 h and further to 0.2 mm/h after 144 h when the soil was saturated (Krantz et al. 1978). The terminal infiltration rates, once the cracks have been sealed and the profile throughly wet, can be extremely slow; common values range from 2.0 mm/h to 0.5 mm/day for a large number of cracking clays of Sudan (Jewitt et al. 1979).

Table 4. Infiltration rates of a typical deep Vertisol[a] at ICRISAT Center, Patancheru, near Hyderabad (India)..

Time from start (h)	Infiltration rates (mm/h)
0-0.5	76
0.5-1.0	34
1.0-2.0	4
After 144 h	0:21 ± 0.1

Source: Krantz et al. (1978).
a. Deep Vertisol is defined as one having a soil depth >90 cm.

During the rainy season, infiltration rates and hydraulic conductivity within the soil control two important water balance components: intake and runoff. Poor drainage can be an inherent physical constraint for crop production on these soils during the rainy season. The necessity of surface adoption of land configuration systems leading to speedy disposal of- excess water was substantiated by the interesting work of Virgo (1981). In Somali, he observed that the cracks in Vertisols tend to join when the profile is wet, leading-to decreased through drainage.

Chemical Properties

Soil pH

As in the case of physical properties, the chemical nature of Vertisols occurring in diverse environments is somewhat similar (Hoskings 1935; Roy and Barde 1962; Virgo and Munro 1978; Jewitt et al. 1979). The Vertisols occurring in India, Australia, Sudan, Ethiopia and other parts of Africa generally have soil pH ranging between 7.5 and 8.5 in the soil profile. Factors which contribute to high soil pH are the presence of $CaCO_3$ and high contents of bases, especially calcium and magnesium, in the profile. The high pH of Vertisols favours gaseous loss of ammonia when urea or ammonium fertilisers are applied to the surface (Terman 1979; Sahrawat 1980). In tropical areas where the soils have either been irrigated or are located in the valleys, the soil reaction may be as high as 9.5 in the surface soil as a consequence of accumulation of exchangeable sodium; in conjunction with their high contents of clay, usually montmorillonite, this has disastrous effects on soil structure.

$CaCO_3$ and Gypsum

Most of the Vertisols are calcareous. The distribution of $CaCO_3$ may be either uniform throughout the profile or may increase in the lower horizons (Raychaudhuri et al. 1963; De Vos and Virgo 1969). The content of $CaCO_3$ in Indian Vertisols may vary from nil to 10% or more in the profile (Roy and Barde 1962). Their calcareous nature along with dominance of montmorillonite clay influences greatly the plant availability of nutrients such as phosphate (Kanwar and Grewal 1960; Nad et al. 1975; More et al. 1978). Gypsum has been found to occur in the sub-surface of the Vertisol profiles in relatively arid areas; its occurrence is a guide to the lack of through leaching by rainfall of the slightly soluble gypsum (Jewitt et al. 1979).

Organic Matter

The dark colour of the Vertisols was earlier suspected to be an indicator of high organic matter content but this was disproved by Singh(1954). Most of the black cotton soils of India rarely have organic matter exceeding 1.0% (Roy and Barde 1962). According to Dudal(1965), the content of organic matter varies from 0.5 to 2.0% in most of the African Vertisols and from 2 to 4% in some Vertisols from the USA (also see Yule and Ritchie 1980a). Some Australian black earths may contain higher amounts of organic matter, up to 6%, in the surface in the semi-arid regions (Williams and Colwell 1977). Similarly, in eight Vertisol profiles from Texas the organic C ranged from 0.63 to 3.21% in the All horizon and generally decreased in the lower horizons (Yule and Ritchie 1980).

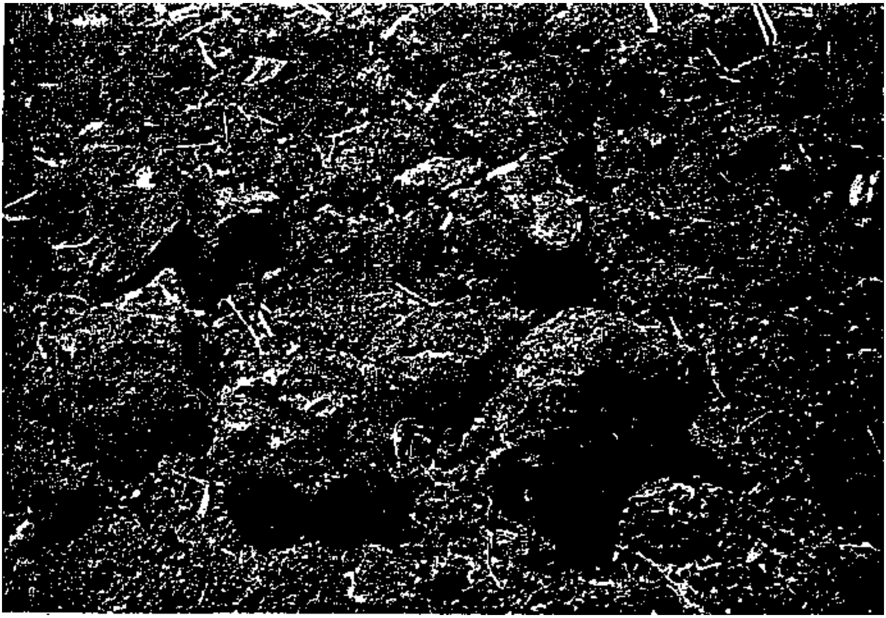
Organic matter has been found to be more or less uniformly distributed in the first metre of the profile in some Indian Vertisols. For example, organic C and total N in the profile of a deep Vertisol at the ICRISAT Center decreased only from 0.45 to 0.31, and from 0.049 to 0.034% respectively in the top 120 cm depth (Table 5).

The organic matter content in Vertisois, as with other soils, is governed by the prevalent vegetation and land-use practices (Dudal 1965), and, pertinent to the tropics, temperature (Jenny and Raychaudhuri 1960). The soils with legumes in their past history have somewhat higher organic matter contents but these decrease due to continuous cropping (Williams and Colwell 1977).

Table 5. Distribution of organic matter and nitrogen with depth in a deep Vertisol at ICRISAT Center, Patancheru, A.P., India.

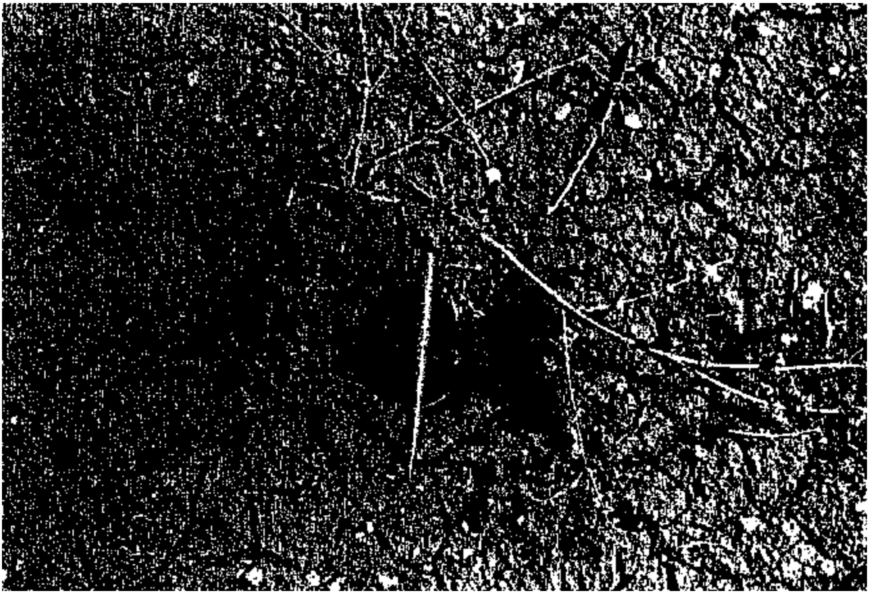
Soil depth (cm)	pH	Organic C	Total N (%)	C/N
0-15	8.35	0.45	0.049	9.2
15-30	8.35	0.41	0.047	8.7
30-45	8.50	0.40	0.042	9.5
45-60	8.45	0.30	0.036	9.1
60-75	8.50	0.31	0.035	8.9
75-90	8.55	0.37	0.034	10.8
90-105	8.75	0.36	0.034	10.5
105-120	8.85	0.37	0.034	10.8

Source; K.L. Sahrawat (unpublished).



Photograph showing an aggregated cloddy structure in a deep Vertisol at ICRISAT Center, Patancheru, near Hyderabad, India.

Photograph showing slickensides in the profile of a deep Vertisol at ICRISAT Center, Patancheru, near Hyderabad, India.



Photograph showing state of cracking on a deep Vertisol at ICRISAT Center, Patancheru, near Hyderabad, India.

Cation Exchange Capacity (CEC)

Because of the usual dominance of 2:1 type clay minerals in the 2 μm particle size fraction, Vertisols are bestowed with higher CEC, although this does depend upon the actual content of clay. Roy and Barde (1962) reported that CEC of the Indian Vertisols ranges between 47 and 65 meq/100 g soil, depending on clay content. Calcium is the most dominant cation accounting for 52 to 85% of the total exchange complex. Magnesium usually ranges from 10 to 30% and sodium is usually less than 20% of total CEC. Vertisols from South Africa, having a clay content of 50 to 60% had a CEC ranging from 50 to 66 meq/100 g soil. Thus, the content of montmorillonite clay in a Vertisol gives an approximate estimate of CEC because 1 g of clay imparts about 0.5 to 0.7 meq of CEC to the soil, and contribution of organic matter towards CEC is quite low in the tropical and SAT regions because of low organic matter contents.

Management of Vertisols in Relation to their Physical and Chemical Properties

From the foregoing listing of some of the properties of Vertisols, it is obvious that this order of soils is potentially one of the most productive in semi-arid regions because it possesses one attribute—high moisture-storage capacity—that is very important in an environment that has unreliable and heavy rains. The major factors responsible for this in most soils are the high content of clay, and the fact that this is usually montmorillonitic. Nevertheless, it is interesting in passing to note that some members still possess the swelling characteristics of Vertisols, whilst containing little "expanding clay" and mainly an illitic/kaolinitic mixture.

The high moisture-storage capacity ensures much safer and more productive cropping; it can assist crops to survive and perhaps even to grow during prolonged dry spells, whereas failures would have resulted on soil not so well endowed. This high moisture-storage capacity will also allow crops to continue to grow for several weeks after the rainy season is ended; it may therefore be possible to grow two crops in 1 year.

However, despite these advantages, these soils have several disadvantages. Although the first rain infiltrates quickly to considerable depths via large cracks, subsequent infiltration and permeability are very low due to the high clay content and poor structure when wet. Drainage may be a problem and crops may become waterlogged. Poor trafficability of the soil when wet seriously interferes with the planting operations. If crops cannot be established during the rainy season in the tropics, the high intensity of the rain on unprotected soil may cause serious erosion.

Such problems are at least part of the reason why farmers in some parts of semi-arid tropical India do not grow a crop during the rainy season, even though the rainfall is sufficiently reliable. This has been overcome by identifying the above problems and by developing management innovations to minimise them: sowing into a dry seedbed ahead of the rains, growing crops on a raised bed to provide drainage and using furrows and waterways to conduct excess water from a watershed.

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